PROOF OF CONCEPT FOR PREDICTION OF PAVEMENT TEMPERATURE:
A TACTICAL DECISION AID FOR HIGHWAY SAFETY

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prepared by
Edward E. Adams, Ph.D.

Department of Civil Engineering
Montana State University
Bozeman, Montana 59715

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16. Abstract

A thermal-mapping program dubbed WinTherm/RT; **Win**dows based **Therm**al Model for **R**oad **T**emperature was developed in this study The computational highway thermal map is an outgrowth of software developed for the U.S. military to determine the infra-red signature of vehicles. This concept uses planar elements of finite thickness called facets to define the geometry. The model developed in this study utilizes U.S. Geological Survey (USGS) digital elevation maps (DEM) and superimposes onto them the highway location. Thermal properties associated with the highway and landscape surrounding it can be assigned. A study plot along I-90 on the west side of Bozeman pass was constructed in this manner. Solar zenith angle, sky view factors, surface to surface radiation exchange and shadowing are taken into account. However, the influence of shadowing in the current algorithm uses a graphical approach that is not producing satisfactory results. This is thought to be the result of the scale necessary for the terrain modeling. In a follow on study this will be replaced with a ray-tracing scheme in order to address the problem. Although data acquisition from the RWIS proved problematic, sufficient information was acquired to yield very promising results.

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SUMMARY

The Montana Department of Transportation (MDT) has had a network of Remote Weather Information Systems (RWIS) installed at what are considered representative locations along the state roadways. Data collected includes standard meteorological parameters such as air temperature, wind velocity, precipitation and relative humidity. Additionally, roadway temperature is measured at the RWIS sites. This information is of vital importance to winter highway operations, due to its obvious influence on highway icing. In an effort to extrapolate the pavement temperature between these measured sites, a "first principles" thermal model was developed as a proof of concept study. In light of the current state of technology and available data, the study was designed to examine the practicality of bringing such a concept to an application level with utility for winter maintenance.

The computational highway thermal map is an outgrowth of software developed for the U.S. military to determine the thermal signature of vehicles. This concept uses planar elements of finite thickness called facets to define the geometry. The model developed in this study utilizes U.S. Geological Survey (USGS) digital elevation maps (DEM) and superimposes onto them the highway location, which was digitally available from MDT. A primary study plot through Rocky Canyon on the west side of Bozeman pass was constructed in this manner. Thermal properties associated with tall grass were assigned to the landscape surrounding the highway for this pilot study. As more detailed geographic information system (GIS) data for vegetation becomes available, it can readily be incorporated into the model. An important concept from the outset is that the program be highly transportable in the sense that another section of highway can be modeled in a straightforward manner. In addition to the information already provided for by the RWIS, radiation data is required for the modeling.

The thermal-mapping program developed in this study is dubbed WinTherm/RT; **Win**dows based **Therm**al Model for **R**oad **T**emperature. The genesis of the code was designed to run under the UNIX operating system, however, it was felt that a p.c. windows environment would have the best potential for application to highway managers. This transition was successfully accomplished, in fact output as a thermal map significantly exceeded expectations. Solar zenith angle, sky view factors, surface to surface radiation exchange and shadowing are taken into account. However, the influence of shadowing in the current algorithm uses a graphical approach that is not producing satisfactory results. This is thought to be the result of the scale necessary for the terrain modeling. In a follow on study this will be replaced with a ray-tracing scheme in order to address the problem. Although data acquisition from the RWIS proved problematic, sufficient information was acquired to yield very promising results.

It is felt that the proof of concept has yielded sufficiently positive results to warrant continued development. A collaborative project between MDT and MSU- has been initiated. WinTherm/RT will be extended in this phase to an operational mode; additional data will be analyzed and refinements implemented.

INTRODUCTION

Icing of pavements is a paramount safety issue in Montana. In an effort to address the problem, the Montana Department of Transportation has established a system of Remote Weather Information System (RWIS) stations that provide site specific meteorological and pavement temperature data. Pavement temperature being of obvious importance to the potential for icing. However, it is virtually impossible to configure the entire highway system with sensors, so extrapolation between sites, by some method, is a necessity. Often, this is intuitively accomplished through vehicle operator or maintenance manager experience. Statistical methods may also be employed to assist. Among the important physical parameters that determine the pavement temperature are topographic variations, such as mountains, valleys, canyons, coulees, and road cuts, and the thermal properties of surrounding landscape. It was proposed to, and accepted by, the Montana Department of Transportation MPART Small Project program that a "proof of concept" study be undertaken to examine the feasibility of developing a "first principles" thermal model to calculate pavement temperature between RWIS sites.

BACKGROUND

The concept behind the modeling effort is based on the adaptation of a computational model used by the U. S. military for the prediction of vehicle infrared images. The genesis of the one dimensional, first principles heat transfer software from which the pavement model is derived is the TCM (Thermal Contrast Model), originally developed for the U.S. Air Force [Johnson, K.R, 1991, Johnson, K.R., et al, 1996.] and PRISM (Physically Reasonable Infrared Signature Model) developed at Michigan Technological University's Keweenaw Research Center in conjunction with the U.S. Army Tank-Automotive Command (TACOM) [*Prism 3.0 User's Manual*, 1991]. These programs were developed as a tool to model the surface temperatures of vehicles for use in infrared imagery. The infrared signature of a vehicle in essence indicates the characteristic surface temperatures of a vehicle subjected to a set of meteorological conditions. Vehicles are composed of homogeneous manmade materials of complex geometry. The modeling approach employed, essentially constructs the three dimensional vehicle by defining a surface composed of a collection of flat plates termed "facets". The landscape in these models was considered simply as background and treated in the model as an isothermal, flat plane.

The facet concept was extended to backgrounds to examine thermal processes in a topologically varied snow cover (Adams and McDowell, 1991 a), including surface condensation and sublimation (Adams and McDowell, 1991 b). Two backgrounds were considered; one of simplified geometry and the other that of a small field on which a detailed elevation grid was surveyed. Recent developments in Geographic Information Systems (GIS), along with the widespread availability of Digital Elevation Maps (DEM) now offer the potential for practical implementation of a terrain model. Highway safety is an area in which pavement temperature is of practical importance. It determines, among other things, ice accretion and it is a vital component in the effective implementation of deicing

and anti-icing programs (Adams et. al., 1991, Adams et. al., 1992, Alger et. al. 1994).

Computationally, one dimensional, finite difference heat conduction equations are solved in the direction of the surface normal, to determine the temperature profile through the thickness of each of the facets. Boundary conditions used to solve the equations assume a fixed temperature for the lower bound and a derivative condition for the heat flux at the upper surface. The upper energy exchange includes solar heating, radiation, convection and phase change. Surface orientation takes into account diurnal solar variation including shadowing, and facet to facet long wave radiation exchange.

Surrounding landscape features including aspect, elevation, and surface material properties, including vegetation, exposed soil, rock or snow all influence the pavement temperatures. The effect that shadowing and surface to surface radiation has on pavement temperature is determined by the thermal properties of the surrounding terrain materials such as albedo, emmisivity, and conductivity. Each facet has a view factor defined, which is in essence what it would "see looking out", given its orientation with respect to the sky and the other facets making up the landscape. These view factors are used to incorporate shadowing, sun angle and the orientation for surface to surface radiation.

The original model was developed on a UNIX based workstation. However, it was felt that if the model were to have wide spread utility to the highway maintenance application, an MS-Windows based format would be the most useful.

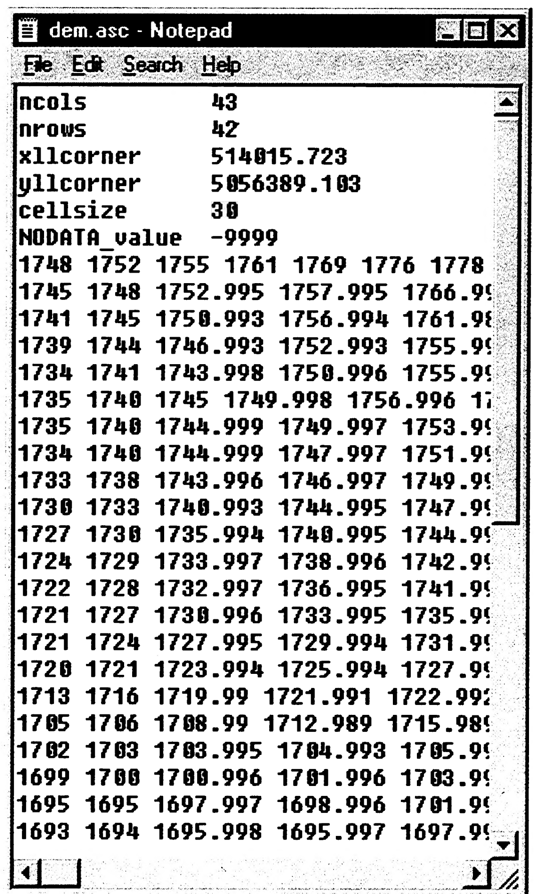
CONSTRUCTING MAPS

The first step in constructing the thermal model is to fabricate maps for the region of interest. It was decided that creating maps in ASCII format would be the most advantageous for long term utility. An important aspect of the development of the model and a driving force in its implementation is that it be fully transportable in the sense that the process developed be easily adaptable to future geographic areas of interest. Working with Montana State University's Geographic Information and Analysis Center (GIAC), GIS's were employed to produce ASCII files for elevation, road and vegetation maps using ESRI's ARC/INFO GIS software. The main pilot study was developed in the Rocky Canyon section of I-90 near Bozeman Pass from milepost 313 to 319.

Several base layers including elevation, roads, mile markers, and vegetation (where available) are required to complete the maps. Only a few years ago development of a model of this sort for widespread application was not feasible due to the lack of a digital GIS information database. Elevation data is now widely available with additional detailed databases for roads, vegetation, soils etc. becoming more widespread. Elevation data were compiled from a United States Geological Survey (USGS) 30 meter DEM. Road and milepost data were available from databases developed by the Montana Department of Transportation. A course vegetation layer originally produced by Fish Wildlife and Parks was downloaded from the NRIS Data Clearinghouse. All data was then projected into the desired coordinate system of UTM meters, NAD83. Maps used in the pilot thermal model used simplified vegetation, which assumed for this proof of concept model development, that the terrain consisted of interstate highway running through grasslands. Future maps can

easily be constructed (and the current one altered) which will utilize more appropriate and varied vegetation.

The procedure to develop the maps using the ARC/INFO software is briefly outlined. The *gridascii* command is used to produce ASCII files of elevation, road and vegetation data. This command extracts the specified values from each grid cell in a grid and lists them in an ASCII file. Header information is included at the top, containing the number of rows and columns, the x-y origin of the lower left corner of the grid, the cell size, and the value used for "no data" in the grid. An example of the data files for the "pilot area 1" map is shown in Figure 1. Two data files are constructed using this process. One is the elevation grid (Figure 1a) and the other a combined roads and terrain grid (Figure 1b). Pilot Area 1 was created as the small initial study that was used to develop the code for the thermal highway mapping. The 43 x 42 grid for this map represents a 1290m x 1260m terrain map. The road and vegetation coverage was first converted to grids using the *linegrid* and *polygrid* commands, respectively. In performing this conversion, the specifications are set to match the elevation grid: the cell size, the grid origin coordinates, and the number of rows and columns. The grids are then combined using a series of functions in *Grid*, including a selection mask, conditional statements, and grid addition. A terrain feature such as an interstate highway, grasslands, forest, sand, water etc. is assigned a number that categorizes it. Note the



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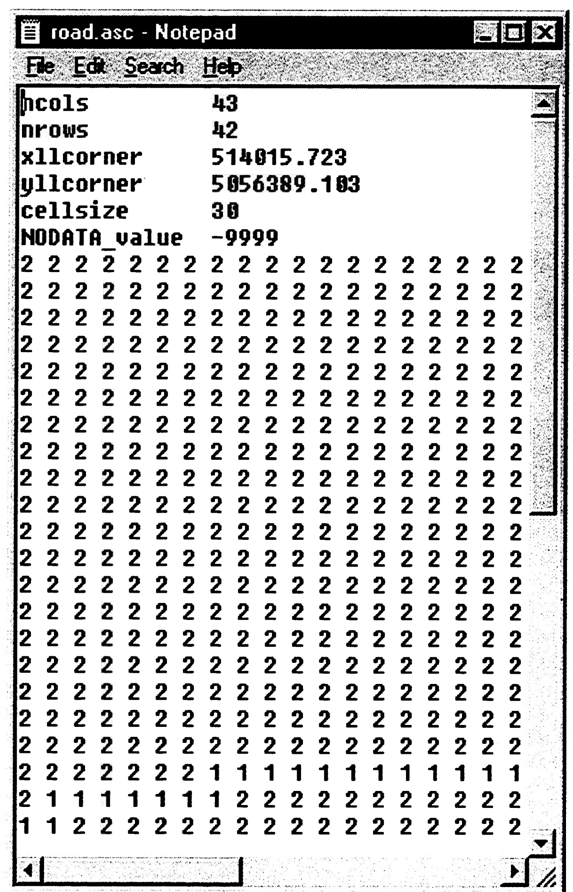

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Figure 1 Example of ASCII input files that are constructed using ARC-INFO. (a) Shows the elevation data derived from USGS 30 m grid. (b) The terrain identification file. Note the 1 indicating the location of the cell where the road is located and the 2 indicates the position of the "other" terrain elements.

numbers 1 and 2 in figure 1b. The UTM coordinates for the milepost coverage were produced by using the *addxy* command. This command simply outputs coordinate values of the x and y locations of each point in the coverage. In the Rocky Canyon pilot map, the eastbound lane mileposts were used in the output file.

WINTHERM/RT

The WinTherm Graphical User Interface (GUI) was developed by ThermoAnalytics for use in parametric studies commonly done by the auto industry [Johnson, K.R., et al, 1995]. The GUI was extended under this project to read digital elevation maps and terrain characteristic files, from which to construct a faceted terrain. The GUI is configured to read the temperature output data generated from the TCM, and to display this information on the faceted terrain. The extended GUI is referred to as WinTherm/RT (**Win**dows based **Therm**al model for **R**oad **T**emperature).

WinTherm/RT predicts and graphically displays road and surrounding terrain temperatures. The inputs to the software include a digital elevation map, an associated terrain characteristics file, meteorological data, and scenario (time/location) information. TCM was extended under this program to account for the effects of solar shadowing, reflections, and re-radiation of terrain features so that temperatures of canyon roads, etc., could be accurately predicted. This was accomplished by utilizing a geometric, or faceted description, of the terrain map from which the necessary solar apparent (shadowed) area and radiation exchange factor of each terrain element are calculated. View factors are calculated from the geometric information using a hardware graphics based Hemicube algorithm.

FILE INPUT

The faceted terrain description is created from a DEM file as described above. The DEM file consists of header lines and grid information. WinTherm/RT reads header lines until the NODATA_VALUE_HEADER line is found (figure 1a). The header lines that must be present in the file are NCOLS_HEADER, NROWS_HEADER, CELLSIZE_HEADER, and NODATA_VALUE_HEADER. The header information (with the exception of NODATA_VALUE_HEADER) is used to create a two dimensional grid, where each grid cell is divided into two triangles (elements). Quadrangular elements cannot be used since the addition of elevation information would cause them to become either non-planar or disconnected from neighboring cells. Planar, connected elements are required for the apparent area and the radiation exchange factor computation. The elevation, or z value of each vertex of each triangle, is determined from the grid information in the file, which is assumed to contain elevation data at the center of each grid cell. The z value of each vertex is taken to be the average of the elevations of the surrounding grid cells. Grid information in DEM files is given starting with the upper left corner of the grid. (Note however that distances in WinTherm/RT's grid are referenced from the lower left corner.)

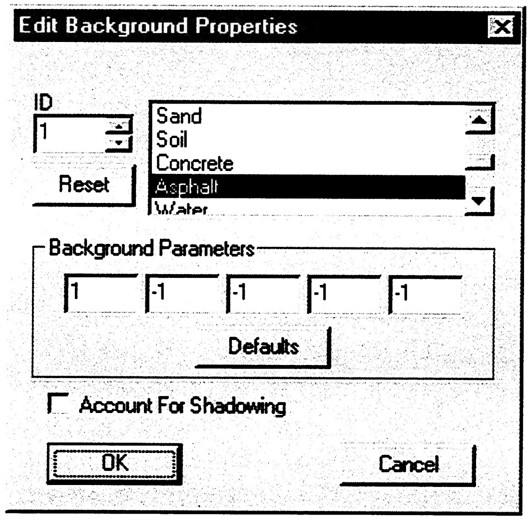


Figure 2 GUI window input mechanism which allows user to associate number tag with terrain material.

The Terrain Characteristics (BkgID) file is assumed to have the same format as the DEM file, except that it specifies a terrain ID at the center of each grid cell (figure 1b). The number is assigned as a specific type of terrain when it is read using the WinTherm/RT GUI (figure 2). The terrain ID is an integer between 1 and 20 (an arbitrary limit set to aid in error detection) that indicates which grid cells have the same characteristics. Inside of WinTherm/RT, all elements having the same terrain ID are referred to as groups. Group 1 (equals terrain ID 1) is given the default properties of asphalt. All other groups are given the default properties of tall grass in the demonstration run.

WINTHERM/RT GRAPHICAL USER INTERFACE

The "File Open" routine loads a modified version of the WinTherm input file, model.in, which stores the names of the DEM and BkgID files. Similarly, the "File New" routine prompts for the DEM and BkgID files, and then stores their names in the model.in file. In both cases, once the file names are obtained, the information in the DEM and BkgID files is read and processed, creating the faceted terrain description.

The "thermal properties" dialog within WinTherm has a dialog that allows the user to assign a terrain type and terrain parameters for each terrain ID read from the bkgID file. This information is then written on a per element basis along with the surface normal to the Scene Description File (SDF). The SDF file, along with a modified solver options file, forms the primary input to TCM.

The user may also choose whether terrain and road temperatures will be calculated strictly from slope and orientation or if shadowing of one part of the terrain by another is to be accounted for. If the shadowing option is selected, radiation exchange factors and shadowed solar apparent areas are calculated using a graphical technique [Curran, A.R., et. al, 1995] and written to disk for use by TCM. (Solar apparent areas are stored in the APA file and radiation exchange factors are stored in the LWX file). These are very computationally expensive calculations that need only to be done once for each digital elevation map.

The thermal node "tracking" capability for WinTherm/RT allows nodes be added to and removed from the list of tracked nodes by clicking on terrain elements in the graphics window. Each triangle in every grid cell is associated with a thermal node placed at the surface of the terrain (and many more below the surface). Due to the large number of nodes in a terrain model, only "tracked" nodes (those nodes for which temperatures are written in tabular form to a data file) are listed in the dialog. To aid users in comparing the temperatures of thermal nodes with temperatures measured at a specific location, two

additional features are incorporated into the Graphical User Interface (GUI). First, each time a terrain element is selected with the mouse, its location relative to the origin of the digital elevation map is displayed in WinTherm/RT's status bar. Second, an edit box and an enter value button were incorporated into the "tracked node" dialog so that once the node number at a particular location is known, it can be typed-in directly. For example, the milepost markers may be associated with the thermal model in this manner

TCM MODIFICATIONS

To account for shadowing, the routine that calculates the solar loading on each terrain element uses the solar apparent area from the APA file and the sky view factor from the LWX file. When the user elects not to account for shadowing, apparent areas and sky view factors are based only on the solar zenith angle. The sky view factor (read from the LWX when shadowing is accounted for) is also used to calculate radiation exchange between each terrain element and the sky. Note, however, that a limitation in the current form of TCM imposes the approximation that, for purposes of calculating radiation exchange between terrain elements, all parts of the terrain are at nearly the same temperature. This has the effect that the net radiative heat transfer between terrain elements is zero in the current version of the model.

To aid in validation, the routines which output the temperatures of tracked nodes were modified to write the temperatures of the sub layers as well as that of the tracked surface node.

THE THERMAL MODEL

In summary, ASCII formatted DEM and GIS terrain material files are read by the WinTherm/RT thermal model. The model then associates the specified numerically categorized material provided by the GIS for each cell to the appropriate properties of that material. These thermal properties (e.g. thermal conductivity, albedo etc.) are applied so that temperatures may be calculated based on the current or forecast environmental conditions. Topography is derived from the DEM. From this are determined the geometric influences including such things as slope and elevation, terrain self-shadow and obscurations, cell-to-cell reflections and emissions and directional solar load on a sloped surface. The first principles thermal model is then employed to calculate the temperatures associated with each cell. Calculated results of the surface temperatures are color linked for display as a time sequence map.

DEMONSTRATIONS

Two examples of a physical-based scene illustrate the ability to produce background predictions that encapsulate true thermal phenomenology.

CHANGING TERRAIN MATERIALS

Figure 3 displays thermal maps of images which were produced using the small "Pilot Area 1" test map. The series of scenes in Figure 3 illustrate how the influence of different material properties can be accounted for with the first principle phenomenological model. This is demonstrated by changing the material properties associated with a specific "tag". In this case, a 1 or a 2. All three of the images are "snapshots" of thermal maps calculated for a set of meteorological conditions at 1200 hours (noon). The color bar at the bottom of each image indicates the full temperature range (10°C to 40°C) set for this particular scene. The intermediate temperature displayed just above the bar represents the temperature of a selected facet indicated by the white triangle near the center of the image. The scene on the left provides the baseline grass terrain in which all facets are considered grass. The temperature of the reference point (future road region) is 23.8°C. In the middle image, the region that is designated as road region is now changed from tall grass (same as the surrounding region) to a sandy road. The new temperature of the road region with this change is now 24.8°C. When asphalt pavement is applied in the model in the right scene, the new temperatures at the same time, location, and conditions as the two previous examples is now 30°C.

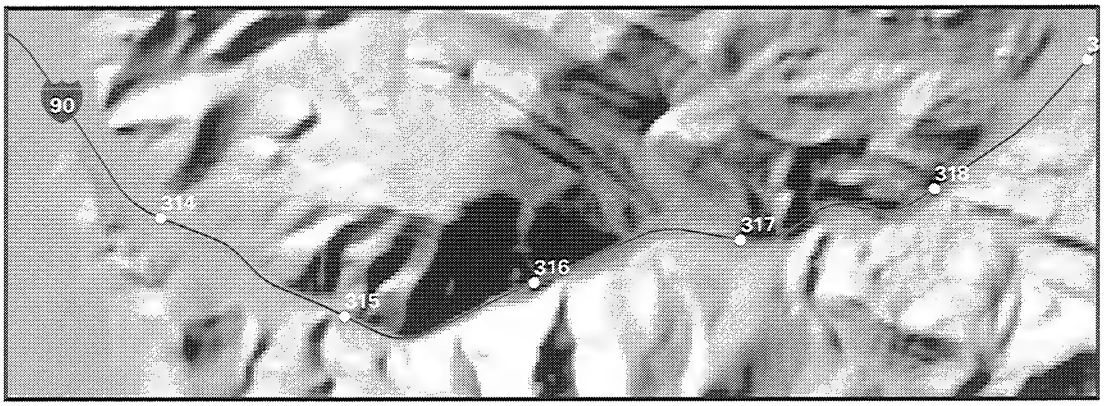
Figure 3. Three similar but altered landscape subjected to the same meteorological conditions (12 noon) are displayed. On the left, a grassy scene is modeled. In the middle image, a sand road had been incorporated. This appears as the lighter shade strip. Finally, the road is modeled as asphalt. The faint white triangle appearing near the center of the road marks the facet correlating with the specific displayed temperature.

DIURNAL CYCLE EXAMPLE

A diurnal cycle for September 2, 1998 on Rocky Canyon, located on the west side of Bozeman Pass, is demonstrated next. A shaded relief map of the 100 by 280 grid, 30-meter DEM cell is shown in figure 4.

Bozeman Pass was selected as the site for the study since it had an established meteorological station and digital data for I-90 was available to superimpose onto the USGS DEM. In addition to meteorological data collected by the RWIS including air temperature,

wind speed, relative humidity and precipitation; radiation is a required input parameter. Although radiation data for the model would ideally include terrestrial as well as solar radiation measurements, a single sensor was chosen to minimize cost for this proof of concept study. Wavelength range for the pyranometer used was 0.400 - 1.1 μm. Terrestrial radiation refers to infrared (4 - 100 μm) emitted from the atmosphere and solar radiation is often used to define visible (0.39 - 0.78 μm) and near-visible radiation. Near visible being the ultraviolet (0.2 - 0.39 μm) and near-infrared (0.78 - 4 μm). The Bozeman Pass RWIS is well-situated regard with regard to an unobstructed view of the sky.



Pilot Area No. 2: Rocky Canyon (MP 315), I90

Figure 4. Map of Rocky Canyon on the west side of Bozeman Pass. DEM and road location data used to produce this scene are the same as the grid used to produce the information for WinTherm/RT.

Figure 5 shows the temperature (Figure 5a) and solar radiation (Figure 5b) data provided to the thermal model. The pyranometer radiation data clearly indicates sunrise to sunset. Note also, the drop in intensity after 1:00 p.m. implying that a cloud obscured the direct solar for a time. The impact is apparent in the model animation displayed in the 18 thermal maps displayed in figure 6. The shadowing option was turned off in this demonstration. The reason for this is discussed below.

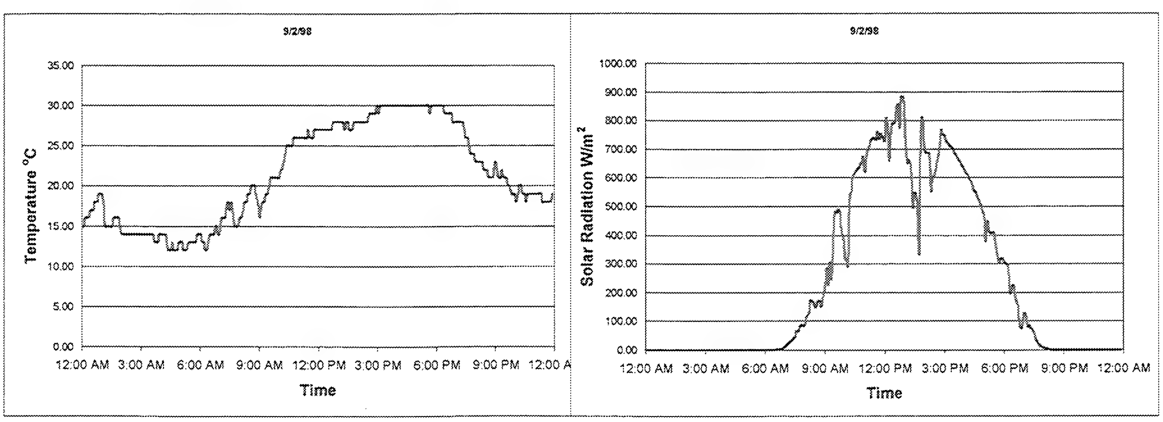


Figure 5 (a) Temperature and (b) solar radiation (0.4 -1.1 μm) data for the Rocky Canyon example.

The color bar temperature range for the series of images in figure 6 is set from 9°C to 39°C. This has the effect of high saturation going white, which emphasizes that highway temperatures are showing spatial temperature variation. Although this is true throughout the day, it is emphasized for these printouts when the color bar is saturated. While this is done for demonstration purposes here, this type of feature might have utility if a particular value is assumed particularly important. For example, if the temperature achieves a value at which chemical treatment might be effective.

In this example, pavement temperature measurements were taken at mile markers 315 through 319 starting at 8:00 a.m. and again starting at 6:00 p.m. A surface contact thermocouple was used to measure the physical temperature. Temperature differences between the calculated and measured were as close as 0.2°C and a maximum difference of 2°C was noted. Wind was light and skies were clear at the time of the measurements. Although only a limited number of verified simulations were accomplished, in those tests the maximum discrepancy was less than 5°C. The largest error occurred when shadowing was in rapid transition.

EVALUATION OF THE PROOF OF CONCEPT

The objective of this proof of concept study was to determine the feasibility of providing a sophisticated computational highway thermal model as a tactical decision aid for use in winter maintenance. Results of this MPART Small Project phase as described in the proposal was not intended for application at its conclusion. Rather it was designed to see if the concept was achievable with current technology and thus warranted further pursuit. The notion is to utilize data collected by highway meteorological stations, in combination with information bases from other existing resources such as the U. S. Geological Survey digital elevation maps (DEM), and geographic information systems (GIS) to calculate pavement temperature. It was anticipated that if the proof of concept was sufficiently meritorious, an implementation phase should be considered.

At this point, we feel that although additional ground truth data is needed to refine the model, the concept is sound and further development justified. In fact, a partial implementation of the second phase of the model evolution has been initiated. A joint MDT/MSU-WTI (Western Transportation Institute) project, entitled "Safe Passage", is being readied on Bozeman pass. The thermal model will assist in this effort by providing motorist travel information as well as allowing highway maintenance personnel to work with and assess the calculated thermal mapping concept. Maintenance managers will then be in a position to provide valuable advice on how the information provided might best be utilized in the operational setting.

Technical problems arose in acquiring and/or accessing data from the RWIS, which unfortunately did not allow for as many verification runs to be accomplished as would have been preferred. In addition to the meteorological data already being collected, radiation data is required to drive the model. Initially, a pyranometer was integrated into the RWIS using an available channel. However, there were problems accessing the sensor output using the RWIS software. Eventually, a separate datalogger was attached to the same

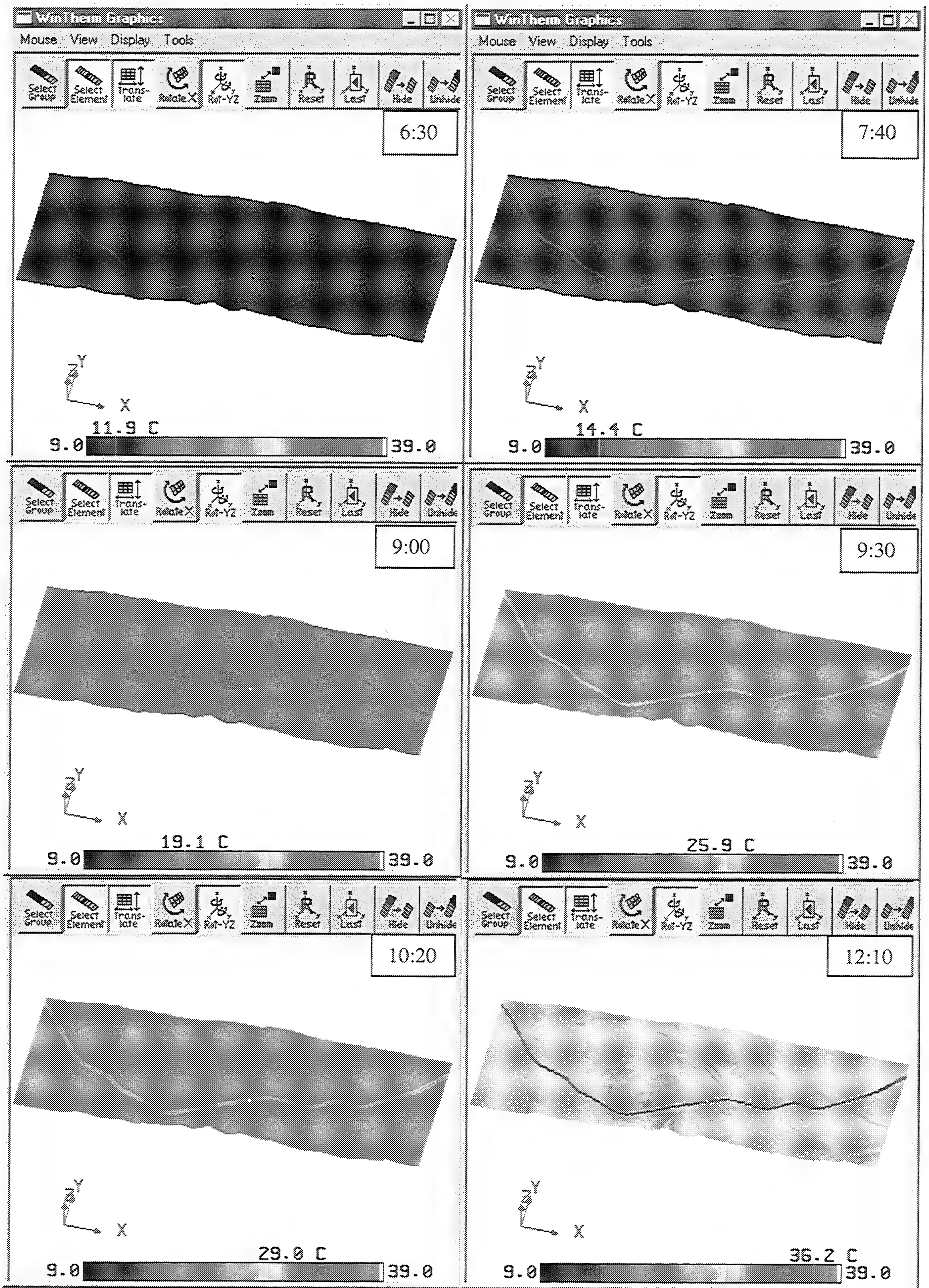


Figure 6. Demonstration of a diurnal cycle using meteorological data from the Bozeman Pass RWIS. Displayed animation times - 6:30, 7:40, 9:00, 9:30, 10:20, 12:10.

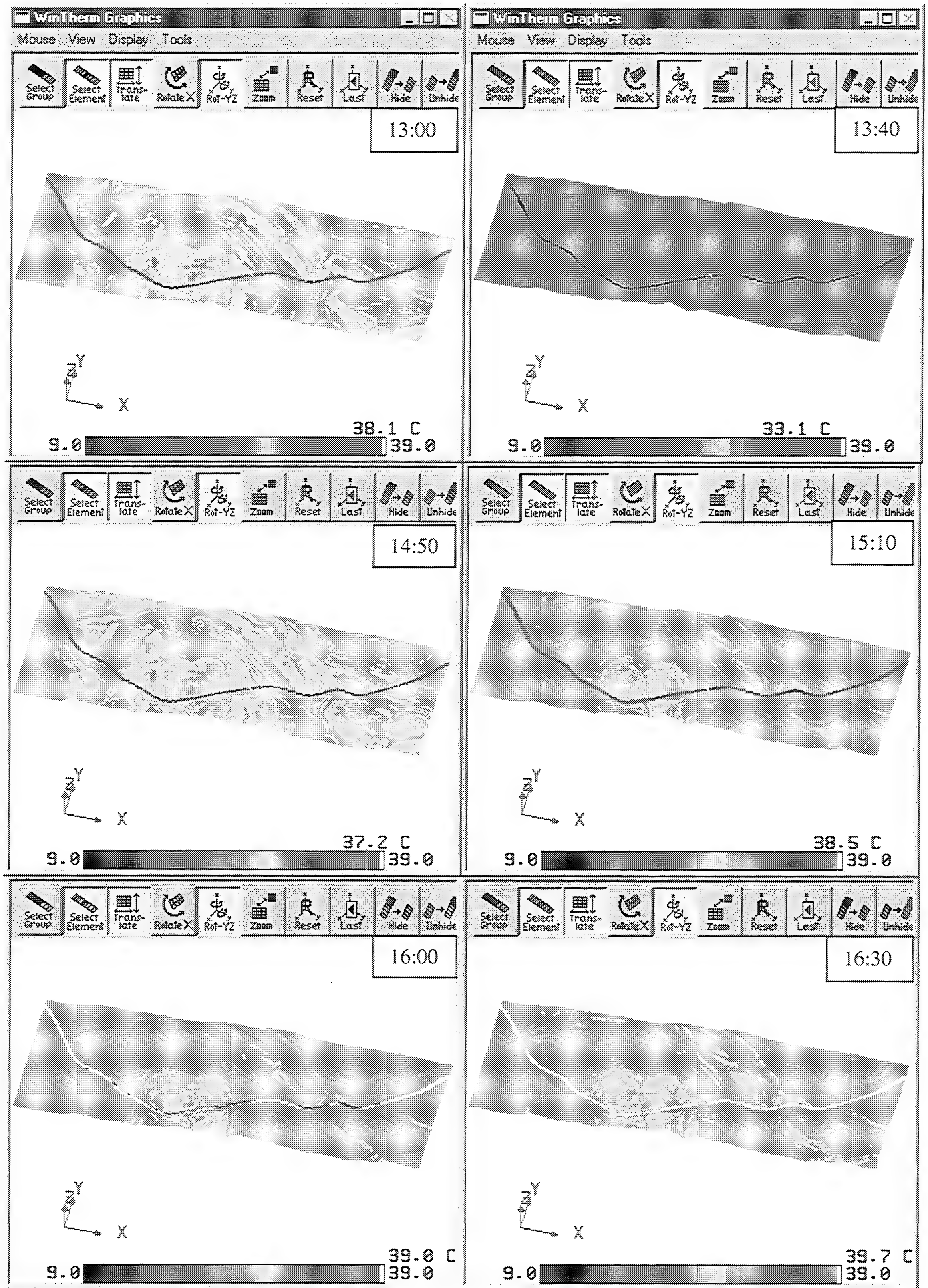


Figure 6 (continued). Demonstration of a diurnal cycle using meteorological data from the Bozeman Pass RWIS. Displayed animation times - 13:00, 13:40, 14:50, 15:10, 16:00, 16:30.

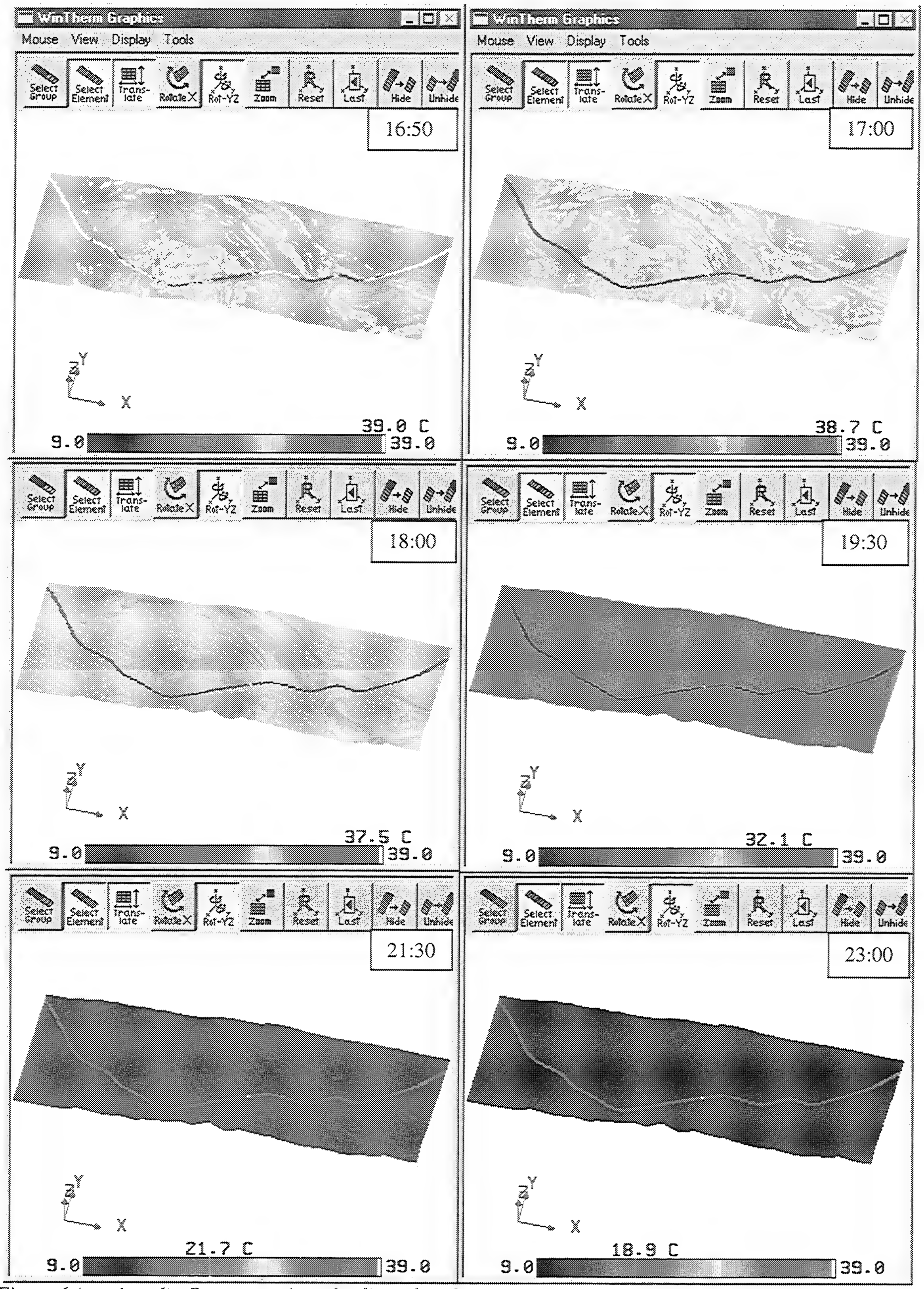


Figure 6 (continued). Demonstration of a diurnal cycle using meteorological data from the Bozeman Pass RWIS. Displayed Animation times 16:50, 17:00, 18:00, 19:30, 21:30, 23:00

tower and radiation data collected independently from the RWIS. This required an on site download. Using the two dataloggers requires the merging of two separate files which proved to be difficult synchronize. The separate datalogger was programmed to take data at a regular 5-minute interval. The software that controls RWIS was not capable of outputting data on a regular interval. This problem with the software required that the two files when combined had to be manipulated manually in an effort to synchronize the time steps. Another problem arose simply from connection problems between the RWIS and the MSU computer.

In addition to material properties, a dominant influence on the spatial variation of calculated temperatures is a function of the orientation of each surface facet toward the sun. This aspect of the model is performing very well. The influence of shadowing of facets by other facets has presented some computational problems when dealing with the required scale of the terrain. The computational problem is likely related to the graphical approach used in the part of the algorithm that defines shadowing. The facet element size is thought to be too large relative to the pixel dimension leading to errors. The concept that will be implemented to rectify the problem will replace this graphical calculation with a "ray trace" approach.
The code was successfully developed to run in the Windows environment. It was expected that at this proof of concept phase output would be in the form of an ASCII data file listing road temperatures. However, in this regard the software development advanced well beyond anticipation. The model presented here includes a graphics capability to provide a shaded visual representation of the calculated surface temperatures for time sequence animation.

We feel that the predictive pavement temperature model presented in this study has displayed sufficient success to warrant further development. Potential remedies for problems as well as enhancements to the model have been identified and will be implemented in the Safe Passage project. The thermal modeling aspect of the Safe Passage project is viewed as the initial implementation phase in an evolutionary engineering process. Timing for the practical application of the model is quite good. Geographic information databases are expanding, which will provide for ease of developing additional sites. Even during the course of this concept study, desktop computers reasonably available to highway managers have significantly increased in capacity and speed. Current progress in mesoscale meteorological models that will provide the data required for forecasting pavement temperature have been maturing in this same time frame. At least one model, which will predict the radiative input, has recently been developed. It would appear that the outlook of the pavement thermal model for development into a useful highway management tool is promising.

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